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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : H04L 25/03, 25/02 | A1

(11) International Publication Number: WO 99/05833

(43) International Publication Date: 4 February 1999 (04.02.99)

(21) International Application Number: PCT/US98/15332

(22) International Filing Date: 27 July 1998 (27.07.98)

(30) Priority Data:
08/901,694 28 July 1997 (28.07.97) US

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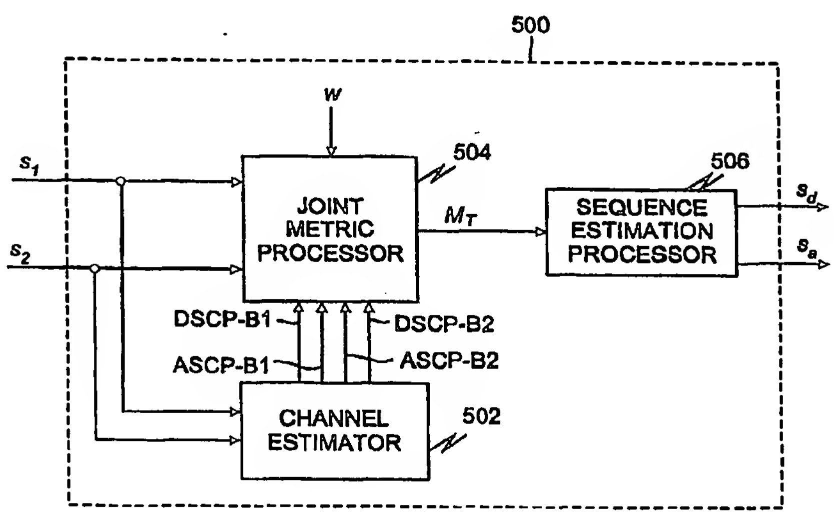
(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, GH, GM, HR, HU, ID, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, UZ, VN, YU, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published
With international search report.

(54) Title: METHODS AND APPARATUS FOR JOINT DEMODULATION OF ADJACENT CHANNEL SIGNALS IN DIGITAL COMMUNICATIONS SYSTEMS



(57) Abstract

Methods and apparatus for receiving adjacent channel signals wherein adjacent channel interference effects are minimized through joint demodulation of the adjacent channel signals. A channel associated with each signal and each corresponding frequency band is estimated and used to form joint branch metrics for joint sequence estimation. In an exemplary embodiment, a baseband processor receives baseband samples corresponding to at least one carrier frequency, and then jointly demodulates at least two information streams corresponding to different carrier frequencies in dependence upon the received baseband samples. In another embodiment, a joint channel estimator receives at least two baseband sample streams, each stream corresponding to a different frequency band, and jointly estimate medium responses for each of at least two information signals which were transmitted in different frequency bands.

METHODS AND APPARATUS FOR JOINT DEMODULATION OF ADJACENT CHANNEL SIGNALS IN DIGITAL COMMUNICATIONS SYSTEMS

BACKGROUND

The present invention relates to digital communications and, in particular, to the demodulation of adjacent channel signals in digital communications systems.

A primary consideration in any digital communications system is the channel bandwidth required to transmit information. Generally, digital systems are designed to utilize channel bandwidth as efficiently as possible. For example, in systems utilizing frequency division multiplexing, maximum spectral efficiency is obtained by spacing frequency channels very close to one another in an available spectrum.

Minimum carrier spacing is limited in practice, however, by adjacent channel interference. As shown in Figure 1, adjacent channel interference is defined as the interference resulting when carrier frequencies are spaced close enough to one another that information signals modulated on the corresponding carriers overlap in the frequency spectrum. In Figure 1, first and second modulated signals $\tilde{s_1}$, $\tilde{s_2}$ having first and second bandwidths B1, B2 are transmitted using first and second carrier frequencies f_1, f_2, respectively. The carrier, or channel, spacing ω between the first and second carrier frequencies f_1, f_2 is such that the first and second modulated signals $\tilde{s_1}$, $\tilde{s_2}$ overlap in a region of interference INT.

In practice, the minimum allowable carrier spacing is a function of the bandwidths of the information signals, the practical limitations associated with receiver filtering, and the signal modulation and coding schemes used. Any design improvement providing increased suppression of adjacent channel interference can be used advantageously to increase system capacity, relax coding and modulation design requirements, or improve signal quality.

In conventional systems, adjacent channel interference is suppressed in a number of ways. For example, in certain cellular radio systems, adjacent channel interference is avoided through channel allocation schemes in which channels immediately adjacent to one another in frequency are assigned to different spacial cells.

Consequently, physical separation reduces mutual interference between adjacent channels. Such a system is described, for example, in *IEEE Transactions on Vehicular Technology*, Vol. 43, November 1994, S. Colestaneh, "The effect of ACI on the capacity of FDMA cellular systems", which is incorporated herein by reference. In other communications systems (e.g., satellite and land mobile radio systems), however, suppression of adjacent channel interference by physical separation of adjacent channels may not be possible.

An alternative conventional approach is described in S. Sampei and M. Yokoyama, "Rejection Method of Adjacent Channel Interference for Digital Land Mobile Communications," *The Transactions of the IECE of Japan*, Vol. E 69, No. 5, pp. 578-580, May 1986, which is incorporated herein by reference. The cited method teaches that, during demodulation of a given carrier signal, a bandpass filter centered at an adjacent carrier is used to extract an adjacent channel signal (ACS) at the adjacent carrier. The extracted signal is then used to estimate the adjacent channel signal envelope and carrier and to coherently detect the adjacent channel signal. The detected adjacent channel signal is then waveform shaped, and the estimated adjacent channel carrier and envelope are impressed on the resulting signal. Ideally, the described process provides a reconstructed adjacent channel signal at its carrier frequency. The reconstructed signal can then be passed through a bandpass filter centered at the carrier of interest and subtracted from the received signal to remove the adjacent channel interference.

Such an approach has several limitations, however. For example, analog signal processing using filters and mixers adds undesirable cost and size to a radio receiver, and since the analog components vary with the manufacturing process, such receivers provide a relatively unpredictable range of performance. Additionally, subtracting a signal at radio frequency requires highly accurate carrier reconstruction and time alignment, as an error as small as half a cycle at radio frequency can cause the adjacent channel signal to double rather than diminish. Furthermore, such use of the adjacent channel carrier (phase and frequency) and envelope (amplitude) implicitly assumes that the radio channels are not dispersive. However, in many practical wireless systems

(e.g., D-AMPS and GSM), the symbol rate is sufficiently high that the radio transmission medium must be modeled to include time dispersion which gives rise to signal echoes. Thus, the proposed technique is not always practical for use in many present day applications.

According to another conventional approach, demodulation parameters such as linear or decision feedback equalization filter coefficients are adapted to minimize noise and adjacent channel interference together. See, for example, *IEEE Transactions on Communications*, Vol. COM-42, December 1994, B.R. Petersen, "Suppression of Adjacent-Channel, Cochannel, and Intersymbol Interference by Equalizers and Linear Combiners". Alternatively, spectrally efficient continuous phase modulation (CPM) techniques can be used to reduce the effects of adjacent channel interference. See, for example, *IEEE Transactions on Communications*, Vol. COM-34, November 1986, V.K. Varma and S.C. Gupta, "Performance of partial response CPM in the presence of ACI and Gaussian noise".

As noted above, however, minimizing or avoiding adjacent channel interference using the above described systems provides only marginal improvement with respect to spectral efficiency, and current suppression mechanisms are inadequate for broad applications. Thus, there is a need for improved methods and apparatus for significantly reducing the impact of adjacent channel interference.

SUMMARY OF THE INVENTION

The present invention fulfills the above-described and other needs by providing a novel radio receiver structure. In an exemplary embodiment, a maximum likelihood sequence estimation receiver jointly estimates desired and adjacent channel parameters and jointly detects desired and adjacent bits. As a result, system performance with respect to adjacent channel interference and capacity is significantly improved as compared to prior art systems.

In an exemplary embodiment, a baseband processor receives a baseband signal including first and second signal components, wherein the first signal component corresponds to a first information signal transmitted in a first frequency band and the

second signal component corresponds to a second information signal transmitted in a second frequency band. The exemplary baseband processor also includes a joint metric processor for computing a joint metric in dependence upon the received baseband signal. Advantageously, the joint metric provides information relating to the first and second information signals, and a sequence estimation processor within the baseband processor provides estimates of the first and second information signals based on the joint metric. As a result, accurate estimates of desired and adjacent signals can be efficiently and accurately obtained, and the effects of adjacent channel interference can be significantly reduced.

The above described and other features of the present invention are explained hereinafter with reference to the exemplary embodiments shown in the accompanying drawings. Those skilled in the art will appreciate that the embodiments are provided for purposes of illustration and that numerous variations are contemplated herein.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 depicts adjacent channel interference between signals modulated using two adjacent carrier frequencies.

Figure 2 depicts a radio communications system in which the teachings of the present invention can be utilized.

Figure 3 depicts a conventional baseband processor.

Figure 4 depicts a baseband processor according to the present invention.

Figure 5 depicts an exemplary embodiment of the baseband processor of Figure 4.

Figure 6 depicts an exemplary joint channel estimator according to the present invention.

Figure 7 depicts exemplary generation of R-parameters used in the joint channel estimator of Figure 6.

Figure 8 depicts an exemplary metric processor according to the present invention.

Figure 9 depicts an alternative embodiment of the baseband processor of Figure 4.

DETAILED DESCRIPTION OF THE INVENTION

Figure 2 depicts a radio communications system 200 in which the teachings of the present invention can be utilized. As shown, the radio system 200 includes a first radio transmitter 202 having a first transmit antenna 206, a second radio transmitter 204 having a second transmit antenna 208, and a radio receiver. The radio receiver includes a receive antenna 210, a radio frequency processor 211, and a baseband processor 218. The radio frequency processor 211 includes a power splitter 212, a first radio processor 214, and a second radio processor 216.

An output of the first radio transmitter 202 is coupled to the first transmit antenna 206 and an output of the second radio transmitter 204 is coupled to the second transmit antenna 208. The receive antenna 210 is coupled to an input of the power splitter 212 and an output of the power splitter 212 is coupled to inputs of the first and second radio processors 214, 216. Outputs of the first and second radio processors 214, 216 are coupled to inputs of the baseband processor 218.

In operation, the first transmitter 202 transmits a first information signal (modulated at a first carrier frequency f_1) from the first transmit antenna 206, and the second transmitter 204 transmits a second information signal (modulated at a second carrier frequency f_2) from the second transmit antenna 208. The transmitted signals reach the radio receiver after passing through a propagation medium (e.g., a mobile radio channel). Both of the transmitted signals, as well as noise, are received at the receiver antenna 210. The received signal is processed by the radio frequency processor 211 to produce a plurality of baseband signals corresponding to the different carrier frequencies f_1, f_2.

Specifically, the power splitter 212 splits the received signal and provides a copy to each of the radio processors 214, 216. The first radio processor 214 amplifies,

mixes, filters, samples, and quantizes the signal to extract a first baseband signal s_1 corresponding to the first carrier frequency f_1, and the second radio processor 216 amplifies, mixes, filters, samples, and quantizes the signal to extract a second baseband signal s_2 corresponding to the second carrier frequency f_2. The resulting baseband signals s_1, s_2 are provided to the baseband processor 218 for demodulation of the transmitted information signals. While a specific radio frequency processor architecture is provided for purposes of illustration, those skilled in the art will appreciate that other known architectures can be used (e.g., wideband digitization followed by digital channelization). Additionally, a single transmitter can be used to transmit on both carrier frequencies f_1, f_2.

Figure 3 depicts a conventional two-channel demodulator 300 which can be included in the baseband processor 218 of Figure 2. As shown, the two-channel demodulator 300 includes a first single-signal demodulator 302 and a second single-signal demodulator 304. The first received baseband signal s_1, corresponding to the first carrier frequency f_1, is coupled to an input of the first single-signal demodulator 302, and the first single-signal demodulator 302 provides a first detected signal s_d. The second received baseband signal s_2, corresponding to the second carrier frequency f_2, is coupled to an input of the second single-signal demodulator 304, and the second single-signal demodulator 304 provides a second detected signal s_a.

In operation, the first received baseband signal s_1 is processed by the first single-signal demodulator 302 using well known techniques to determine the channel parameters and information bits transmitted at the first carrier frequency f_1. Similarly, the second received baseband signal s_2 is processed by the second single-signal demodulator 304 to determine the channel parameters and information bits transmitted at the second carrier frequency f_2. Significantly, demodulation of the two information signals is entirely decoupled, and the conventional demodulator is susceptible to adjacent channel interference effects as described above.

Figure 4 depicts a two-channel demodulator 400 constructed in accordance with the present invention. As shown, the two-channel demodulator 400 includes a joint multi-signal demodulator 402 receiving first and second baseband signals s_1, s_2 as input

and providing first and second detected signals s_d, s_a as output. In operation, both baseband signals s_1, s_2 are used to jointly demodulate each transmitted information signal as described below. It should be noted here that the solution provided by the present invention (i.e., joint demodulation of information signals transmitted in adjacent frequency bands) is markedly different from conventional systems providing joint demodulation of co-channel information signals transmitted in a common band. Joint demodulation of co-channel signals using a single baseband signal is described for example in *IEEE Proceedings on Communications*, Vol. 142, No.2, April 1995, S.W. Wales, "Technique for co-channel interference suppression in TDMA mobile radio systems" and in *Proceedings of IEEE International Conference on Communications (ICC)*, 1995, P.A. Ranta, "Co-channel Interference Canceling Receiver for TDMA Mobile Systems". However, joint demodulation of co-channel signals is relatively easy to accomplish since co-channel signals occupy the same frequency band and therefore do not require symbol correction that depends upon the spacing between carriers. Additionally, only a single radio processor is employed in such systems. By way of contrast, the present invention is directed to methods and apparatus for jointly demodulating information signals transmitted in multiple frequency bands.

Figure 5 depicts an exemplary embodiment of a multi-signal demodulator constructed in accordance with the present invention. As shown, the two channel demodulator 500 includes a channel estimator 502, a joint metric processor 504, and a sequence estimation processor 506. The first received baseband signal s_1 is coupled to a first input of the joint metric processor 504 and to a first input of the channel estimator 502. The second received baseband signal s_2 is coupled to a second input of the joint metric processor 504 and to a second input of the channel estimator 502. The channel estimator 502 provides four channel parameter estimates DSCP-B1, ASCP-B1, DSCP-B2, ASCP-B2 which are coupled to four corresponding inputs of the joint metric processor 504. The four channel parameter estimates correspond to the desired signal response in the first band B1, the adjacent signal response in the first band B1, the desired signal response in the second band B2, and the adjacent signal response in the second band B2, respectively.

The carrier spacing ω is coupled to an additional input of the joint metric processor 504, and a joint metric M_T provided by the joint metric processor 504 is coupled to an input of the sequence estimation processor 506. The sequence estimation processor 506 provides the first and second detected signals s_d, s_a as output, where it is assumed for purposes of illustration that the information signal transmitted on the first carrier frequency f_1 is the desired signal and the information signal transmitted on the second carrier frequency f_2 is the adjacent signal (i.e., the interfering signal in the first band B1).

In operation, joint metrics are developed in the metric processor 504 as is described in more detail below. Advantageously, the joint metrics can incorporate multiple carriers as well as multiple antennas. The joint metrics utilize channel tap coefficient estimates for both desired (i.e., in-band) and interfering signals. The channel tap estimates are provided by the channel estimator 502. The resulting joint metric M_T is provided to the sequence estimation processor 506, and the sequence estimation processor 506 provides estimates of the desired and adjacent information sequences s_d, s_a. Specifically, the sequence estimation processor 506 performs maximum likelihood sequence estimation (MLSE) based on the joint metric M_T.

Advantageously, the maximum likelihood sequence estimation provides an optimum detection algorithm in the presence of inter-symbol interference (ISI) and additive white Gaussian noise (AWGN). In the exemplary embodiment, the maximum likelihood sequence estimation is implemented in a re-cursive manner, for example using the Viterbi algorithm described in *Proceedings of the IEEE*, Vol. 61, March 1973, G.D. Forney, "The Viterbi Algorithm", which is incorporated herein by reference. Alternatively, the complexity of the maximum likelihood sequence estimation processor can be reduced by employing a suboptimum reduced-state Viterbi equalizer. Other known suboptimum equalization techniques can also be utilized. See, for example, *IEEE Transactions on Vehicular Technology*, Vol. 16, 45, August 1996 , J. Wu and H. Aghvami, "A New Adaptive Equalizer with Channel Estimator for Mobile Radio Communications", which is incorporated herein by reference.

Further processing may follow the sequence estimation processor 506. For example, de-interleaving, decoding and conversion to speech typically follow sequence estimation in digital cellular systems. In this case, the sequence estimation processor 506 may also provide soft information relating to the reliability or likelihood of true bit values. When coding and interleaving is across frequency bands, joint decoding using both outputs of 506 can be used.

For the channel estimation process carried out by the channel estimator 502, data sequences can be inserted periodically into the transmitted information sequences at the transmitters 202, 204. Such data sequences, commonly called synchronizing sequences, are known at the receiver, and different sequences are used for the desired signal and each adjacent signal. The channel estimation, therefore, can be carried out using the synchronizing sequences and other known parameters. Generally, least square estimation (the most common and efficient method in the presence of additive white Gaussian noise) can be used to estimate the channel parameters. A novel joint channel estimation scheme is described in detail below.

It is assumed in the description that channel estimates obtained during transmission of the synchronizing sequences are held constant during subsequent transmission of information sequences (until transmission of the next synchronizing sequences). It is possible, however, to adapt the channel estimates using known adaptive channel estimation methods. See, for example, G.E. Bottomley and S. Chennakeshu, "Adaptive MLSE equalization forms for wireless communications", Virginia Tech's Fifth Symposium on Wireless Personal Communications, May 31-June 2 1995, which is incorporated herein by reference. Furthermore, if synchronizing sequences are not provided, known blind channel estimation techniques may be employed. Those skilled in the art will appreciate that the following joint channel estimation scheme is but one scheme which can be used in the joint demodulation approach taught by the present invention.

To provide the channel estimates, certain features of the transmitters 202, 204 and the radio processors 214, 216 are modeled. For example, information symbols are typically passed through pulse shaping filters prior to transmission. The pulse shapes

are often selected such that the transmitted signal will have a compact power spectrum, and the pulses typically extend more than one symbol interval (i.e., partial response pulse shaping). In the radio processors 214, 216, receiver filters are typically selected such that they collect signal energy. If the radio channel, or medium, is modeled as another filter, then a received baseband signal can be expressed generally as a convolution of the information symbols which are transmitted in the corresponding frequency band with the overall effects of the transmitter pulse shapes *tx*, the medium response *g*, and the receiver filters *rx* as follows:

$$\text{received signal} = \text{transmitted symbols} \otimes (tx \otimes g \otimes rx) \qquad (1)$$

where $\otimes$ indicates the convolution operation. As noted above, the synchronization symbols, the transmit pulse shapes, and the receiver filters are known at the receiver. However, the medium response *g* changes with the environment and is therefore estimated dynamically so that the information symbols can be estimated more accurately. Thus, equation (1) can be more conveniently written such that the known terms are grouped together and the unknown term *g* is separated as follows:

$$\text{received signal} = [\text{transmitted symbols} \otimes (tx \otimes rx)] \otimes g \qquad (2)$$

To facilitate explanation of the invention, the baseband-symbol-spaced samples resulting from the convolution of the transmit pulse shapes *tx* and the receiver filters *rx* are designated hereinafter as the $\mathbb{R}$ parameters, and the samples resulting from the convolution of the $\mathbb{R}$ parameters with the synchronizing symbols in the baseband are designated hereinafter as the $\mathbb{X}$ parameters. Note that all of the parameters are obtained in the baseband since the signals s_1, s_2 provided as input to the multi-signal demodulator 500 are baseband signals. As a result, rotations based on the carrier spacing ω (which is known or estimated at the receiver) are used in obtaining local replicas of the desired and adjacent signals and the corresponding parameters. Such rotation is described in more detail below.

Figure 6 depicts an exemplary embodiment of a joint channel estimator 600 which can be used to implement the channel estimator 502 of Figure 5. As shown, the

joint channel estimator 600 includes an X-parameter processor 602 having first and second rotation devices 606, 608 and four R-parameter devices r_{21}, r_{11}, r_{22}, r_{12}. The joint channel estimator 600 also includes third and fourth rotation devices 610, 612, a combined joint least square estimator 614, and first and second couplers 616, 618. Synchronization bits for the first baseband signal s_1 are provided to an input of the first rotation device 606 and to the second R-parameter device r_{11}. Synchronization bits for the second baseband signal s_2 are provided to the third R-parameter device r_{22} and to an input of the second rotation device 608.

The carrier spacing ω is provided to a second input of the first rotation device 606, and an output of the first rotation device 606 is coupled to an input of the first R-parameter device r_{21}. The carrier spacing ω is also provided to a second input of the second rotation device 608, and an output of the second rotation device 608 is coupled to an input of the fourth R-parameter device r_{12}. A first X-parameter x_{21} output by the first R-parameter device r_{21} is coupled to an input of the third rotation device 610, and a fourth X-parameter x_{12} output by the fourth R-parameter device r_{12} is coupled to an input of the fourth rotation device 612. Second and third X-parameters x_{11}, x_{22}, output by the second and third R-parameter devices r_{11}, r_{22}, respectively, are coupled to inputs of the combined joint least square estimator 614.

The carrier spacing ω and a tap count L (corresponding to the number of channel coefficients, or taps, used to model the medium responses) are coupled to inputs of the third rotation device 610. An output of the third rotation device 610 is coupled to an input of the combined joint least square estimator 614. The carrier spacing ω and the tap count L are also provided as inputs to the fourth rotation device 612. An output of the fourth rotation device 612 is coupled to an input of the combined joint least square estimator 614. The combined joint least square estimator 614 receives the first and second baseband signals s_1, s_2 and provides estimates g_1, g_2 of the first and second medium responses (corresponding to the first and second transmitted signals, respectively). The first medium response estimate g_1 is coupled to the first coupler 616 which produces two channel parameter estimates DSCP-B1,

FIG. 1

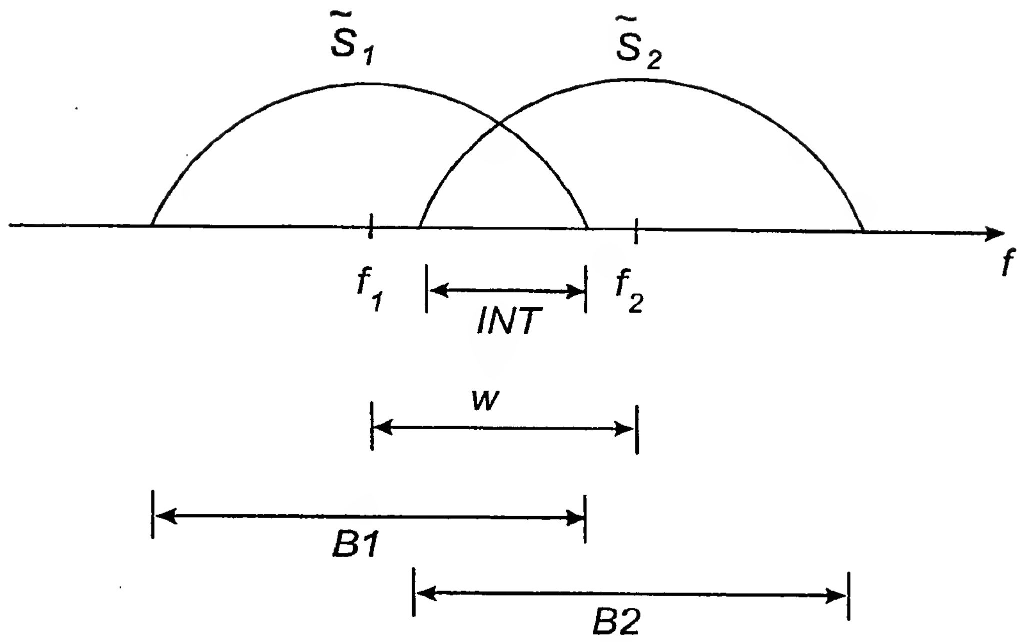
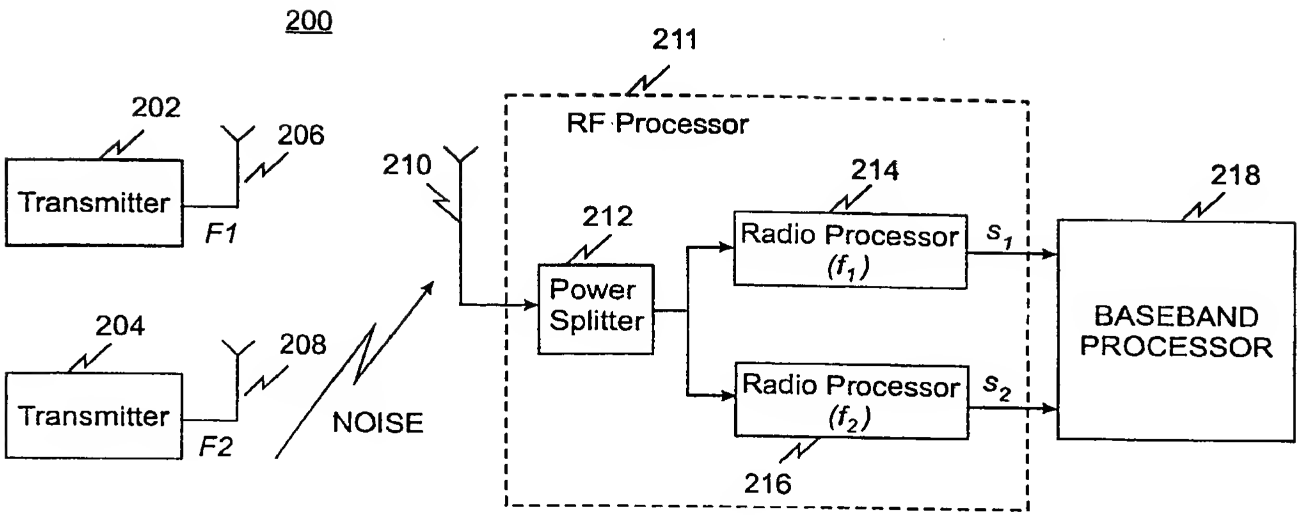


FIG. 2



200
202
Transmitter
206
F1
204
Transmitter
208
F2
NOISE
210
211
RF Processor
212
Power Splitter
214
Radio Processor (f_1)
216
Radio Processor (f_2)
s_1
s_2
218
BASEBAND PROCESSOR

FIG. 3
(PRIOR ART)

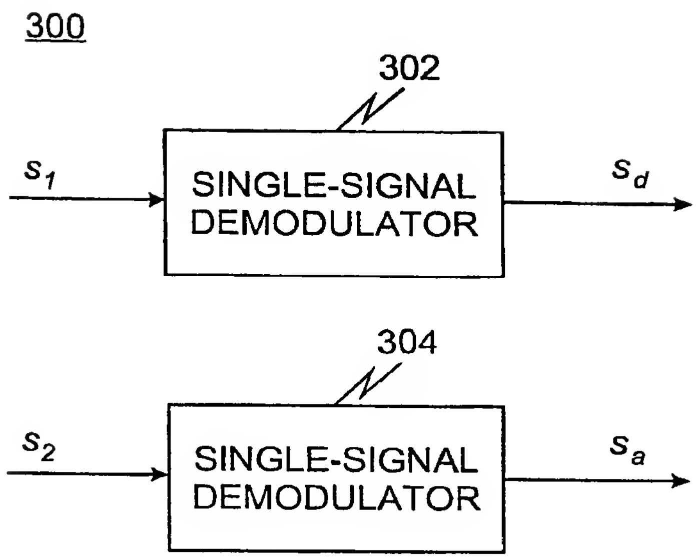


FIG. 4

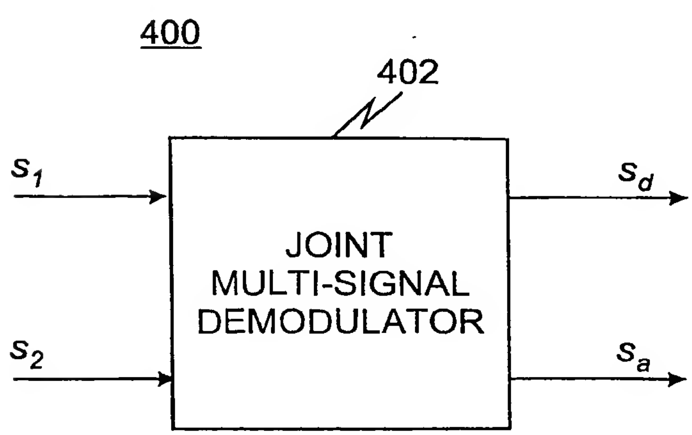
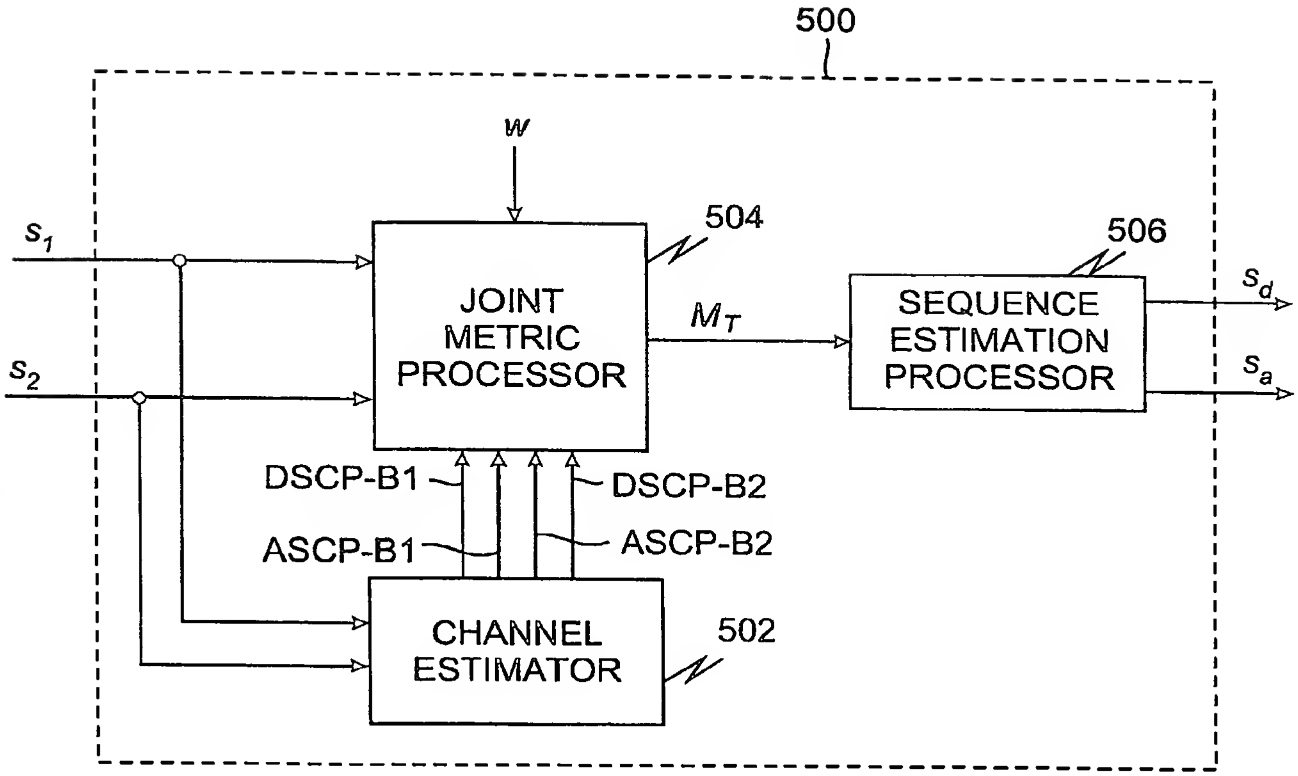


FIG. 5


500
W
504
506
s_1
s_2
JOINT
METRIC
PROCESSOR
M_T
SEQUENCE
ESTIMATION
PROCESSOR
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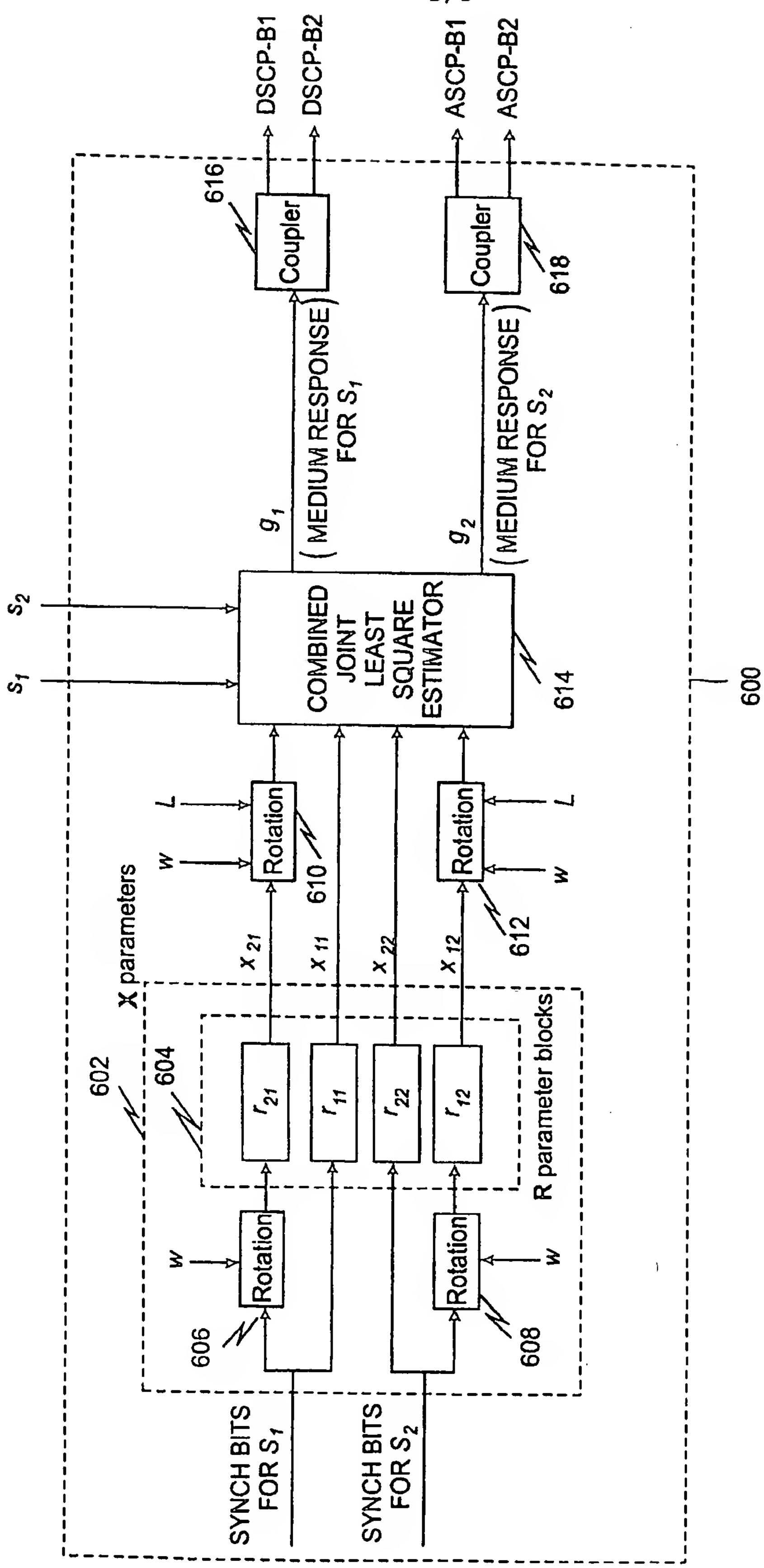
s_a
DSCP-B1
DSCP-B2
ASCP-B1
ASCP-B2
CHANNEL
ESTIMATOR
502

FIG. 6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ASCP-B2
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Coupler
Coupler
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g_2
(MEDIUM RESPONSE FOR S_2)
s_2
s_1
COMBINED JOINT LEAST SQUARE ESTIMATOR
614
600
L
w
Rotation
610
Rotation
L
w
612
X parameters
x_{21}
x_{11}
x_{22}
x_{12}
602
604
r_{21}
r_{11}
r_{22}
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Rotation
Rotation
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606
608
SYNCH BITS FOR S_1
SYNCH BITS FOR S_2

FIG. 7

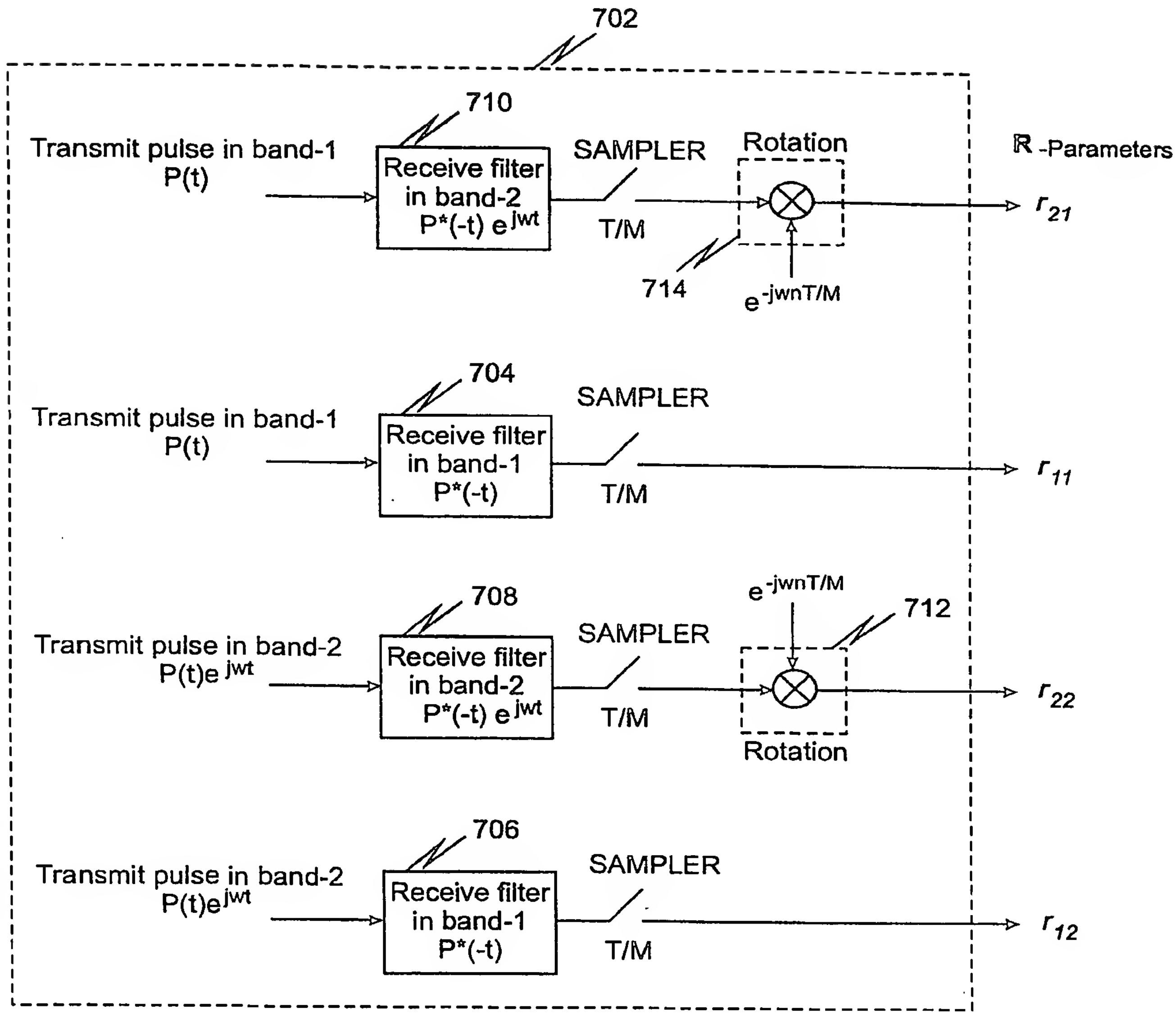
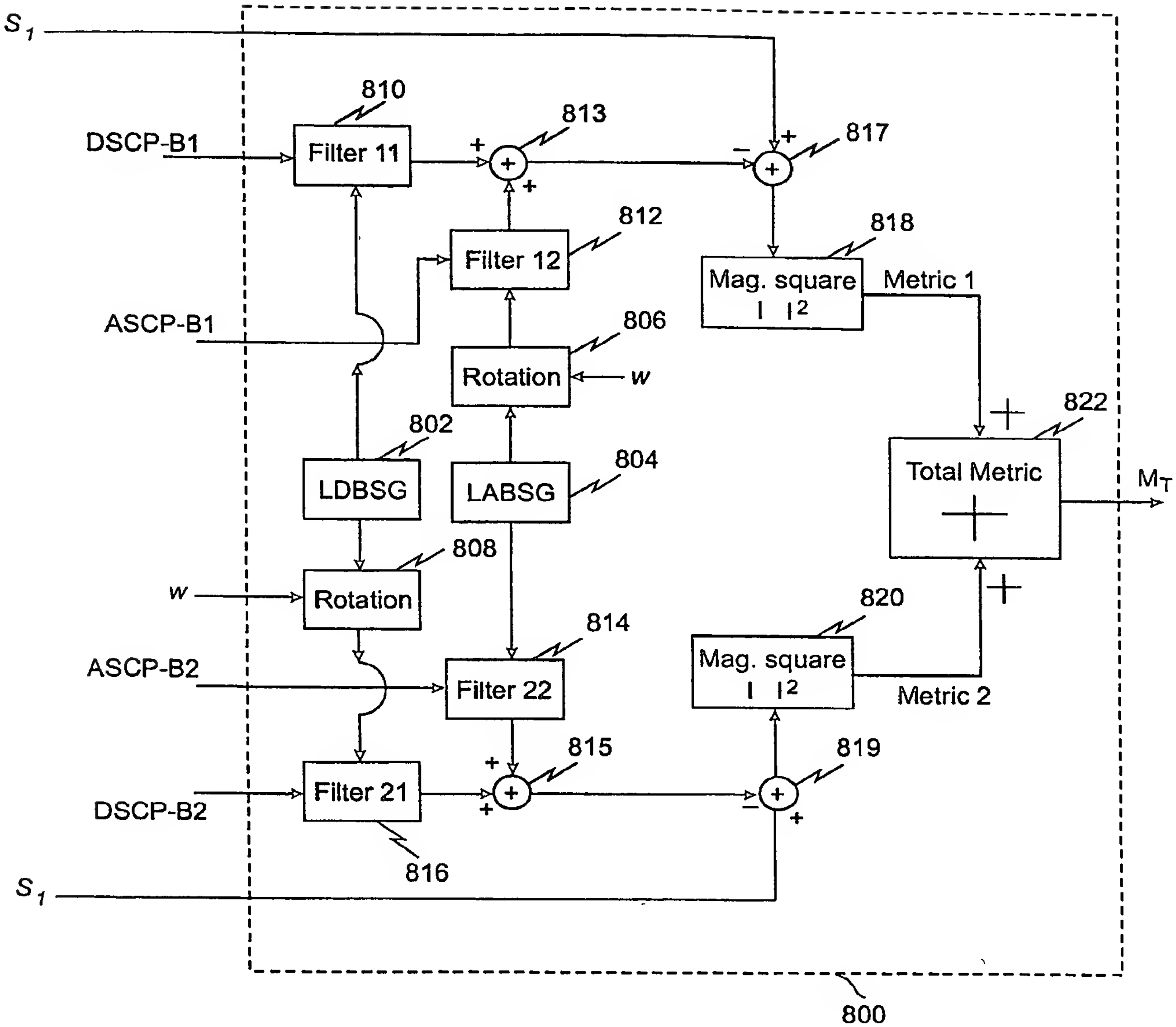

702
710
Transmit pulse in band-1
P(t)
Receive filter
in band-2
P*(-t) e jwt
SAMPLER
T/M
Rotation
714
e -jwnT/M
R -Parameters
r 21
704
Transmit pulse in band-1
P(t)
Receive filter
in band-1
P*(-t)
SAMPLER
T/M
r 11
708
Transmit pulse in band-2
P(t)e jwt
Receive filter
in band-2
P*(-t) e jwt
SAMPLER
T/M
e -jwnT/M
712
Rotation
r 22
706
Transmit pulse in band-2
P(t)e jwt
Receive filter
in band-1
P*(-t)
SAMPLER
T/M
r 12

FIG. 8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810
Filter 11
813
817
812
Filter 12
818
Mag. square
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Metric 1
ASCP-B1
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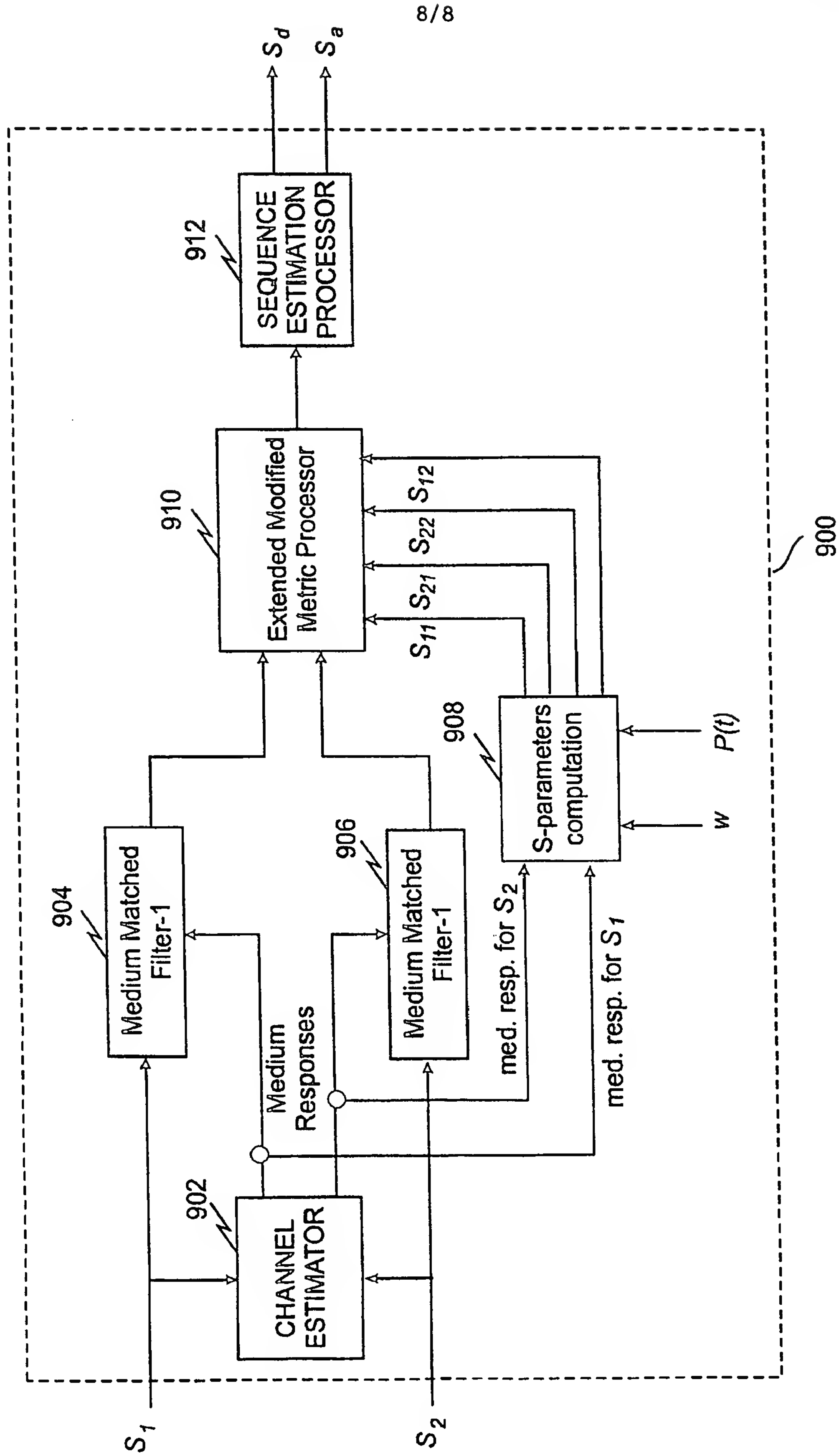
Rotation
w
802
804
LDBSG
LABSG
822
Total Metric
MT
808
w
Rotation
820
814
ASCP-B2
Filter 22
Mag. square
| |2
Metric 2
815
819
Filter 21
DSCP-B2
816
S1
800

FIG. 9


S1
S2
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Medium Responses
Medium Matched Filter-1
904
Medium Matched Filter-1
906
med. resp. for S2
med. resp. for S1
S-parameters computation
908
w
P(t)
Extended Modified Metric Processor
910
S11
S21
S22
S12
SEQUENCE ESTIMATION PROCESSOR
912
Sd
Sa
900